

Antipodean fugitive terranes in southern Laurentia: How Proterozoic Australia built the American West

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ABSTRACT

Paleoproterozoic arc and backarc assemblages accreted to the south Laurentian margin between 1800 Ma and 1600 Ma, and previously thought to be indigenous to North America, more likely represent fragments of a dismembered marginal sea developed outboard of the formerly opposing Australian-Antarctic plate. Fugitive elements of this arc-backarc system in North America share a common geological record with their left-behind Australia-Antarctic counterparts, including discrete peaks in tectonic and/or magmatic activity at 1780 Ma, 1760 Ma, 1740 Ma, 1710–1705 Ma, 1690–1670 Ma, 1650 Ma, and 1620 Ma. Subduction rollback, ocean basin closure, and the arrival of Laurentia at the Australian-Antarctic convergent margin first led to arc-continent collision at 1650–1640 Ma and then continent-continent collision by 1620 Ma as the last vestiges of the backarc basin collapsed. Collision induced obduction and transfer of the arc and more outboard parts of the Australian-Antarctic backarc basin onto the Laurentian margin, where they remained following later breakup of the Neoproterozoic Rodinia supercontinent. North American felsic rocks generally yield Nd depleted mantle model ages consistent with arc and backarc assemblages built on early Paleoproterozoic Australian crust as opposed to older Archean basement making up the now underlying Wyoming and Superior cratons.

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INTRODUCTION

Competing reconstructions of the Nuna and Rodinia supercontinents in which the 1800–1600 Ma terranes of southern Laurentia (Mojave, Yavapai, and Mazatzal provinces) are juxtaposed against basinal sequences of comparable age in eastern Australia or Antarctica commonly assume that these various rock packages are indigenous to their respective continental margins and once lay opposite each other (Betts et al., 2016; Borg and DePaolo, 1994; Burrett and Berry, 2000; Karlstrom et al., 2001). Opposing rock packages are not only thought to have formed along a single continuous convergent plate margin but preserve a common record of arc magmatism and back-arc extension interspersed with episodes of collision during the course of which one or more magmatic arc assemblages and their host basins were accreted, beginning as early as 1780 Ma and continuing through to at least 1600 Ma (Betts et al., 2016; Bickford and Hill, 2007; Karlstrom et al., 2001; Whitmeyer and Karlstrom, 2007). Successive collisional events transformed this accretionary margin into a trans-continental orogenic belt, making it one of the principal constraints on supercontinent reconstructions (Karlstrom et al., 2001). However, as studies of the 1710 Ma Bonnetia terrane in present-day northwest Canada have recently shown (Furlanetto et al., 2013; Thorkelson and Laughton, 2016), not all late Paleoproterozoic magmatic arc assemblages accreted to the Laurentian margin need have North American origins (cf. Nordsvan et al., 2018) or have formed proximal to this margin. Some, like Bonnetia, are believed to have Australian affinities and can only have been accreted

to the opposing Laurentian margin following closure of one or more intervening ocean basins (Thorkelson and Laughton, 2016). The possibility that other North American terranes, including those accreted along its southern margin, may similarly have originated distal to Laurentia (Gibson et al., 2018, 2008) and include fugitive arcs from the opposing Australia-Antarctic continental margin cannot be discounted and has far-reaching implications for existing reconstructions of the Nuna supercontinent and the assumptions that underpin them. More specifically, previous suggestions that Proterozoic eastern Australia-Antarctica remained connected to Laurentia from before 1800 Ma until at least 1650 Ma (e.g., Betts et al., 2006) may not be correct. Instead, the two continents may have evolved independently of each other throughout this period before being brought together in continent-continent collision no later than 1600 Ma. Here, we show that this interpretation is not only consistent with known geological similarities between rocks of 1800–1600 Ma age on both continents but provides a plausible explanation for the observation that their underlying basement rocks share near-identical age and isotopic compositions.

BASIN EVOLUTION AND MAGMATISM ALONG EAST AUSTRALIAN-ANTARCTIC RIFTED MARGIN

From 1800 to 1600 Ma, the eastern margins of formerly conjoined Archean–Proterozoic crustal blocks in Australia and Antarctica (Fig. 1A) were subjected to widespread lithospheric extension and thinning, resulting in basin formation, granite intrusion, and copious amounts of coeval volcanic activity now represented by thick piles of tholeiitic basalt and rhyolite variably metamorphosed from greenschist up to the granulite

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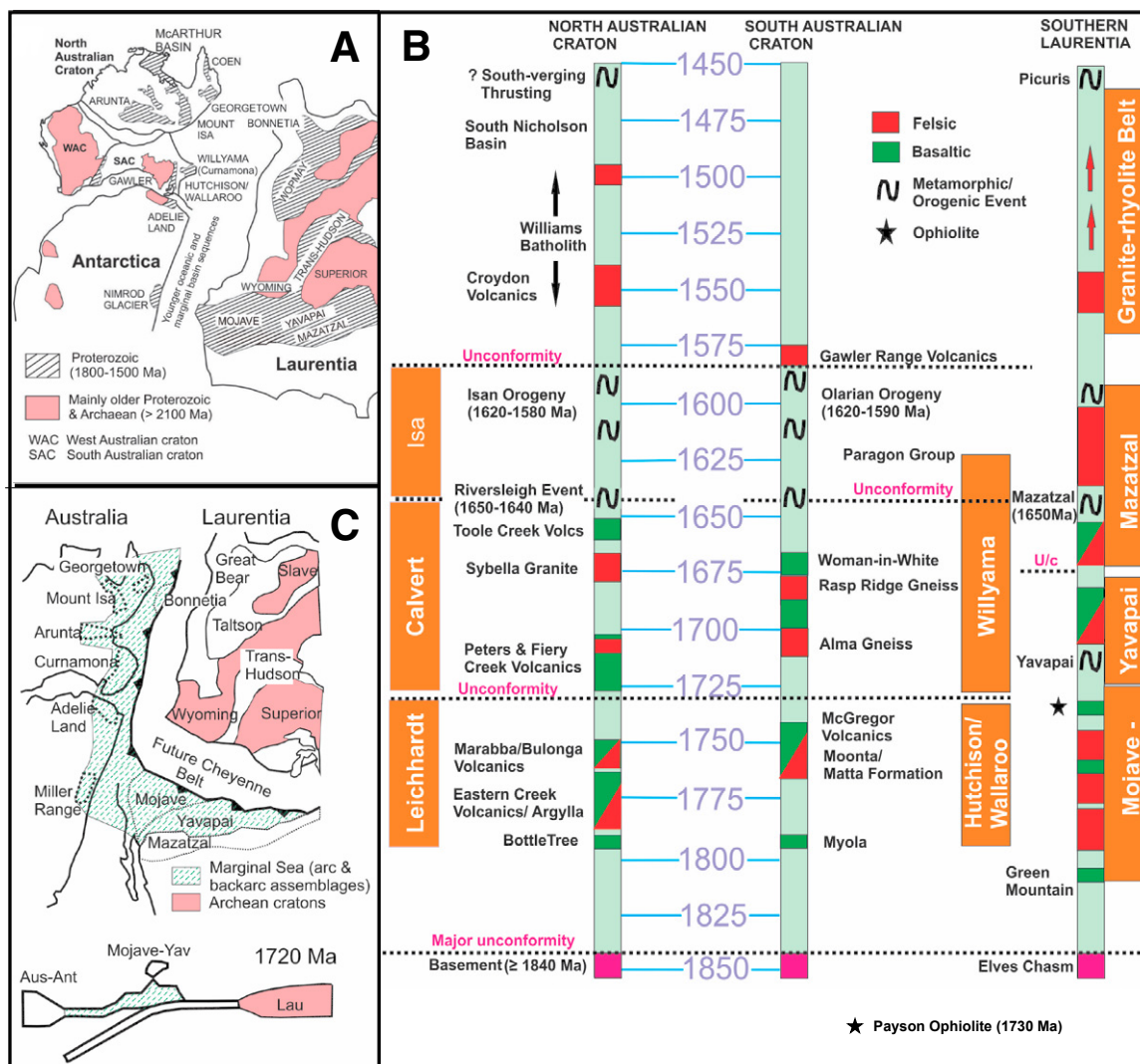


Figure 1. (A) Distribution of 1800–1600 Ma basinal sequences in Paleoproterozoic eastern Australia-Antarctica versus their temporal equivalents in western Laurentia subsequent to 1600 Ma but before Rodinia breakup commenced ca. 830 Ma. Position of Australia relative to Laurentia is indicative only and assumes Mojave was originally connected to east Antarctica (e.g., Borg and DePaolo, 1994) rather than Curnamona Province as in some other reconstructions (Burrett and Berry, 2000). **(B)** Bar code record of principal 1850–1450 Ma magmatic and tectonic events across basinal sequences and crustal provinces for Australian and North American continental blocks shown in A. **(C)** Mojave and Yavapai crustal provinces in their original position along the opposing Australian-Antarctic convergent margin ca. 1720 Ma. The Mazatzal Province has yet to form but occupies a future backarc position inboard of the magmatic arc represented by the Yavapai Province.

facies (Gibson et al., 2018; Willis et al., 1983; Wyborn et al., 1987). More than half of the 8–10 km-thick 1790–1740 Ma Leichhardt Superbasin (Fig. 1B) in the Mount Isa and McArthur River regions is composed of greenschist facies metavolcanic rocks, and further thick accumulations of metamorphosed basalt and rhyolite have been reported from the temporally equivalent Wallaroo and Hutchison groups along the eastern margin of the Gawler craton (Cowley et al., 2003; Fanning et al., 2007; Szpunar et al., 2011). Significantly, volcanic rocks in both these sequences were erupted at roughly similar times and in similarly discrete pulses at 1790 Ma, 1780 Ma, 1760 Ma, and 1740 Ma (Fig. 1B). Compositions of basaltic rocks erupted at these times are also very similar, showing moderately high enrichment in lithophile elements coupled to conspicuous depletions in high field strength elements like Nb, P, and Ti, consistent

with melting of a metasomatically enriched or crustally contaminated lithospheric mantle (Gibson et al., 2018; Gregory et al., 2008; Scott et al., 2000). Geochemical and isotopic analyses for these and other basaltic rocks compared in this study are listed in Tables DR1 and DR2 in the GSA Data Repository Item¹.

Based on substantial amounts of interstratified quartzite, sandstone, and more limited amounts of dolostone, it is further evident that the bulk

¹GSA Data Repository Item 2019236, Table DR1: Whole rock geochemical analyses for basaltic rocks in Yavapai and Mazatzal provinces sorted according to reported age and volcanic assemblage; Table DR2: Whole rock Sm-Nd isotopic analyses for felsic igneous rocks of western USA (Proterozoic to Cenozoic), is available at <http://www.geosociety.org/datarepository/2019>, or on request from editing@geosociety.org.

of basaltic rocks as well as most rhyolites were erupted into a depositional environment where sedimentation kept pace with subsidence and persistently occurred under fluvial to shallow marine conditions. A tectonically unstable intracontinental rift environment characterized by episodic but ongoing backarc extension seems likely for much of this magmatism, consistent with the observation that basin fill in the Leichhardt Superbasin was demonstrably laid down in half-graben or fault-bounded asymmetric basins (Bain et al., 1992; Betts et al., 2006; Derrick, 1982; Gibson et al., 2008; O'Dea et al., 1997) and, like the Hutchison Group (Szpunar et al., 2011), incorporates considerable volumes of sedimentary rock derived from local or proximal older continental sources. These sources include 1870–1840 Ma basement granites and felsic gneisses exposed in the neighboring Leichhardt-Kalkadoon block of Mount Isa and correlative Donnington Suite farther south (Szpunar et al., 2011) as well as a contingent of older rocks dating back to the Archean (2.7 and 3.3 Ga) and derived from more distal crustal sources across the North Australian and Gawler cratons (McDonald et al., 1997; Neumann et al., 2006). Felsic gneisses are predominantly of volcanic origin which, together with the granites, are thought to have been emplaced into an arc-like tectonic environment at or subsequent to conclusion of the 1890–1870 Ma Barramundi Orogeny in the older host rocks (Bierlein et al., 2008; McDonald et al., 1997). This basement was then extensively intruded by dolerite dykes during development of the Leichhardt Superbasin and from seismic reflection profiles would appear to extend eastwards at depth as far as the

Georgetown Province but in increasingly attenuated form (Gibson et al., 2016; Korsch et al., 2012).

With formation of the younger 1730–1640 Ma Calvert Superbasin (Fig. 1B), the area subjected to rifting, bimodal magmatism, and lithospheric thinning greatly expanded to include not only the Mount Isa and McArthur River regions, but neighboring Georgetown Province (Etheridge Group), eastern Curnamona Craton (lower Willyama Supergroup), and central Transantarctic Mountains (Miller Range and Nimrod Complex) as well. Fluvial-shallow marine conditions persisted during bimodal magmatism at ca. 1730–1720 Ma and 1710–1705 Ma in most areas (Fig. 1B) although, by 1690–1670 Ma, quartzite was no longer the dominant sedimentary host rock and depocenters were increasingly filled with thin-bedded sandstones and siltstone in the west and deep marine turbidites farther east (Southgate et al., 2013; Withnall and Hutton, 2013). Turbidite deposition was accompanied by the intrusion of dolerite dykes and sills (Soldiers Cap and Kuridala groups), and at deeper structural levels by the emplacement of syn-extensional A- and S-type granites (Neumann et al., 2006). Coincidentally, basaltic rocks started to become increasingly less contaminated in crustal components (Figs. 2A and 2B) and more MORB-like in composition as the underlying lithospheric mantle was either replaced by less metasomatically enriched sources or had become so vanishing thin as to allow the asthenosphere to rise to much shallower levels than during Leichhardt time. In either event, basaltic magmatism in a turbidite-filled deep marine basin continued until 1655 Ma (Fig. 1B)

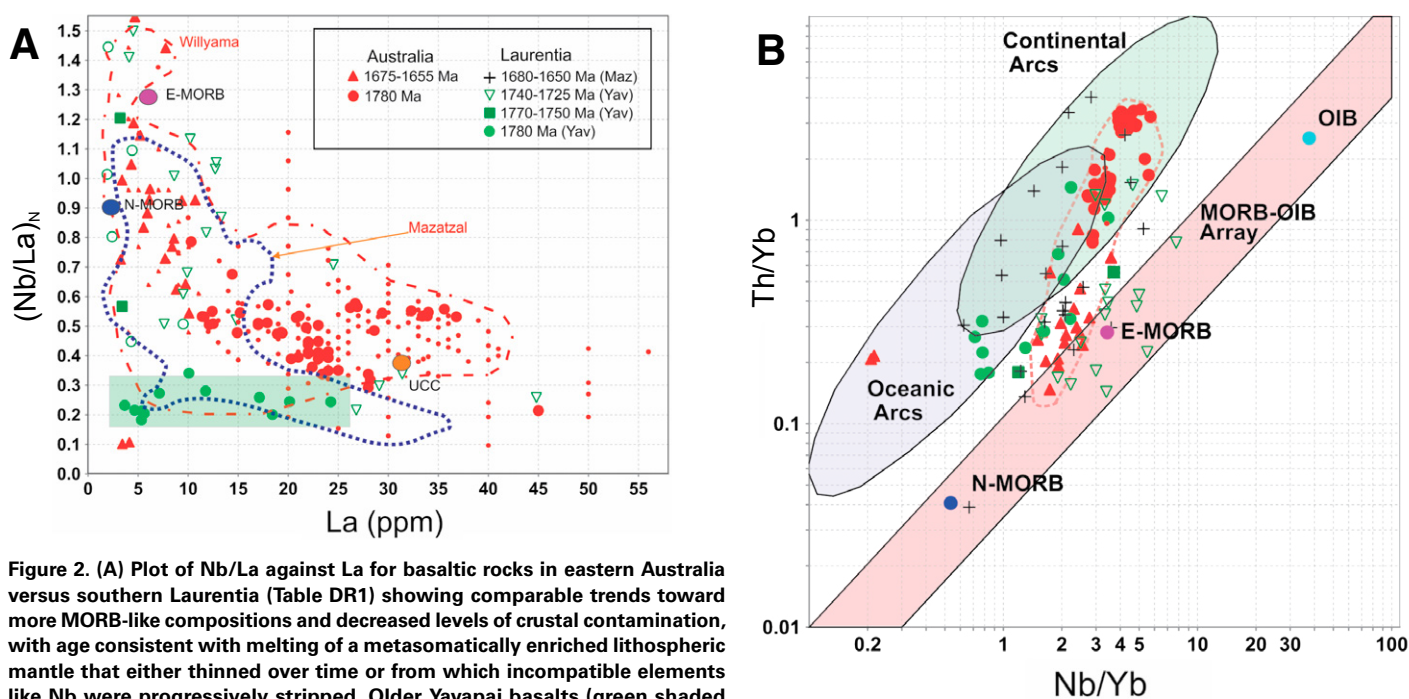


Figure 2. (A) Plot of Nb/La against La for basaltic rocks in eastern Australia versus southern Laurentia (Table DR1) showing comparable trends toward more MORB-like compositions and decreased levels of crustal contamination, with age consistent with melting of a metasomatically enriched lithospheric mantle that either thinned over time or from which incompatible elements like Nb were progressively stripped. Older Yavapai basalts (green shaded area) plot separately from other rocks in the province and consistently give low Nb/La values more akin to those obtained in continental arc settings as has been previously proposed (Bickford and Hill, 2007; Whitmeyer and Karlstrom, 2007). To avoid unnecessary clutter, compositional data for the Willyama Supergroup and Mazatzal province have been collectivized (broken line polygons) rather than plotted individually. (B) Th/Yb vs Nb/Yb plot as proxy for level of crustal contamination in basaltic rocks (Pearce, 2014) from same regions. Basaltic rocks from the 1780 Ma Leichhardt Superbasin are more crustally contaminated than those farther east (Georgetown) in the Calvert Superbasin and show the same trend as in A toward more MORB-like compositions with age. Conversely, older basalts in the Yavapai province have a very different trajectory and mainly plot in the arc field above the MORB-OIB array consistent with formation in a magmatic arc setting; only basalts toward the younger end of the age spectrum plot within the MORB-OIB array. Compositional data plotted in the two diagrams were compiled from the literature (Table DR2) and include analyses obtained by both ICPMS (large symbols) and XRF (small symbols). North American geochemical analyses from Bryant et al. (2001), Condie and Nuter (1981), Copeland and Condie (1986), Jones et al. (2011), Knoper and Condie (1988), Meijer (2014), Robertson and Condie (1989), Australian data from Geoscience Australia database, Gregory et al. (2008), and Rutherford et al. (2006). NMORB and EMORB from Sun and McDonough (1989) and UCC (average upper crustal composition) from Rudnick and Gao (2004).

by which time crustal thinning and backarc extension are thought to have concluded, leaving the basinal sequences of Proterozoic eastern Australia and Antarctica lying along the inboard side of a marginal sea, not unlike those observed today in the western Pacific (Gibson et al., 2018). At this point, the magmatic arc that had been developing off the Australian-Antarctic margin since at least 1800 Ma severed all connection with the latter and now lay isolated on the opposing side of this same backarc basin. With the conclusion of rifting and onset of passive margin conditions, the entire east Australian-Antarctic seaboard began to thermally subside and was blanketed by a transgressive sequence of post-rift marine sediments, including black carbonaceous shales, dolomitic siltstones, and stromatolite-bearing carbonate rocks. The deepest part of this sequence was deposited in Georgetown and the eastern part of the Curnamona province, which then served as the trailing edge of the Australian-Antarctic continent. This common record of basin formation and shared geological history (Gibson et al., 2018) would appear to preclude alternative interpretations in which the Georgetown Province is postulated to have originated in western North America (Boger and Hansen, 2004; Nordsvan et al., 2018; Pourceau et al., 2018).

Following, and possibly partly overlapping deposition of this post-rift sedimentary package, much of the Australian-Antarctic margin was again subjected to increased amounts of tectonic instability from ca. 1650 Ma until 1640 Ma (Fig. 1B), triggering basin inversion, widespread folding, and internal redistribution of sedimentary rocks in response to local uplift and erosion (Gibson et al., 2017; Scott et al., 1998; Southgate et al., 2000). These events make up part of the Riversleigh Tectonic Event (Withnall and Hutton, 2013) and were likely accompanied by crustal thickening as evidenced by the local preservation of relict higher pressure mineral assemblages yielding ca. 1650 metamorphic monazite ages (Abu Sharib, 2012; McFarlane and Frost, 2009; Rubenach et al., 2008). These ages have been reported from both the Calvert Superbasin and lower Willyama Supergroup and in the eastern Mount Isa region (Soldiers Cap Group) derive from rocks in which kyanite and garnet overprint an earlier-formed layer-parallel fabric thought to be primarily of extensional origin (Abu Sharib, 2012). Arc-continent collision subsequent to rifting and backarc extension has been invoked as one possible explanation for these higher pressure mineral assemblages (Gibson et al., 2017).

Subsequent to crustal thickening, a further several kilometers of deep marine sediment were deposited in the 1640–1580 Ma Isa Superbasin (Fig. 1B) and uppermost part of the Willyama Supergroup (Paragon Group). Basaltic rocks are completely absent and sedimentation has been variously attributed to post-rift thermal subsidence, development of a foreland basin, or deposition in extensional basins formed during gravitational collapse of previously overthickened crust (Betts and Lister, 2002; Dunster and McConachie, 1998; Gibson et al., 2017). Irrespective of origin, this basin, along with parts of the previously deposited Leichhardt and Calvert superbasins, was subsequently intruded by 1600–1590 Ma granites and deformed under low pressure–high temperature metamorphic conditions during the same orogenic event from 1620 to 1580 Ma (Withnall and Hutton, 2013). Various known as the Isa or Olary orogeny in northern and southern Australia (Willis et al., 1983; Withnall and Hutton, 2013), this event temporally overlaps the North American 1650–1600 Ma Mazatzal Orogeny or a younger 1620 Ma phase within the latter long thought to mark the time when the Mojave, Yavapai, and Mazatzal crustal provinces became fully assembled and were re-accreted to the Laurentian margin (Amato et al., 2008; Whitmeyer and Karlstrom, 2007). In the alternative interpretation presented here, accretion and orogenesis are transmuted into the arrival and docking of arc and backarc assemblages rifted off the opposing Australian-Antarctic margin. Accordingly, in our model, these supposedly indigenous North American crustal provinces can never have

been built on Laurentian lithosphere and might be expected to preserve a geological and magmatic record more in accord with the basinal sequences they left behind than ancestral North America.

This is not dissimilar to conclusions drawn for Bonnetia whose 1710 Ma magmatic arc assemblage and underlying substrate are also thought to have originated off eastern Australia before being obducted over the opposing Laurentian margin during the ca. 1600 Ma Racklan Orogeny (Thorkelson and Laughton, 2016). The Racklan Orogeny is the same age as the Mazatzal Orogeny, leading some researchers to propose that the obduction of Bonnetia was matched elsewhere around Laurentia by the accretion of indigenous North American terranes to form a single circum-Laurentian collisional belt (Furlanetto et al., 2013, 2016; Verbaas et al., 2018). As with Gibson et al. (2008), these researchers rejected previous suggestions that this accretionary orogen once continued into central Australia (Betts et al., 2016, 2008; Giles et al., 2002; Karlstrom et al., 2001) but apparently gave little or no consideration to the possibility that the accreted terranes of southern Laurentia may themselves have originated on the opposing continental margin and be similarly of Australian origin.

LAURENTIAN TERRANES AS FUGITIVES FROM OPPOSING AUSTRALIAN-ANTARCTIC MARGIN

As in Proterozoic eastern Australia, the period from 1800 Ma until 1600 Ma in southern Laurentia (Fig. 1B) was one of episodic but ongoing tectonic instability accompanied by widespread bimodal magmatic activity and formation of three stratigraphically discrete crustal packages, viz: the 1790–1640 Ma Mojave, 1780–1710 Ma Yavapai, and 1680–1600 Ma Mazatzal provinces (Bickford and Hill, 2007; Bickford et al., 2015; Holland et al., 2018; Whitmeyer and Karlstrom, 2007; Wooden et al., 2013). The Mojave Province (Fig. 1A) was intruded by granite in two separate episodes (1790–1740 Ma and 1710–1650 Ma) and comprises variably deformed igneous and sedimentary rocks whose 1790–1740 Ma protoliths (Wooden et al., 2013) are essentially the same age as rocks making up the Leichhardt Superbasin (Fig. 1B). Detrital zircon ages dating back to 3.3 Ga, lower ϵNd values and Sm-Nd depleted mantle model ages of 2.0–1.8 Ga and 2.7–2.4 Ga (Fig. 3) from these same rocks further indicate that the Mojave Province is isotopically more evolved than other parts of southern Laurentia (Bennett and DePaolo, 1987; Whitmeyer and Karlstrom, 2007; Wooden et al., 2013) and more like Paleoproterozoic eastern Australia (average 2.2–2.4 Ga), both of which are thought to have formed through the erosion and recycling of underlying, but largely unexposed older Paleoproterozoic and/or Archean basement (Fig. 1A). Interpolated maps of Sm-Nd depleted mantle (DM) model ages (Fig. 3) also show strikingly similar trends with calculated values serving as a proxy for crustal age or lithospheric thickness and decreasing eastward in tandem with crystallization ages in igneous rocks from both continents. In Australia, this eastward decrease in Sm-Nd DM model ages (Fig. 3A) is manifestly linked to lithospheric thinning and accompanying deepening of the sedimentary basin as evidenced by seismic data (Gibson et al., 2016; Korsch et al., 2012) and the onset of shallow to deep marine carbonate sedimentation at the expense of quartzite (Gibson et al., 2018), whereas in the Mojave Province, where quartzite is rare, this same trend occurred at a time of deeper water turbidite deposition (Vishnu Schist) (Holland et al., 2018; Wooden et al., 2013). Significantly, turbidites in the Mojave province are extensively intruded by dolerite with enriched compositions (Wooden et al., 2013) not unlike the basalts making up substantial volumes of the Leichhardt Superbasin (Gibson et al., 2018). As such, the Mojave Province and Leichhardt Superbasin are unlikely to have evolved independently of each other but were originally underlain by a common lithospheric mantle and occupied complementary positions within the same arc-backarc setting.

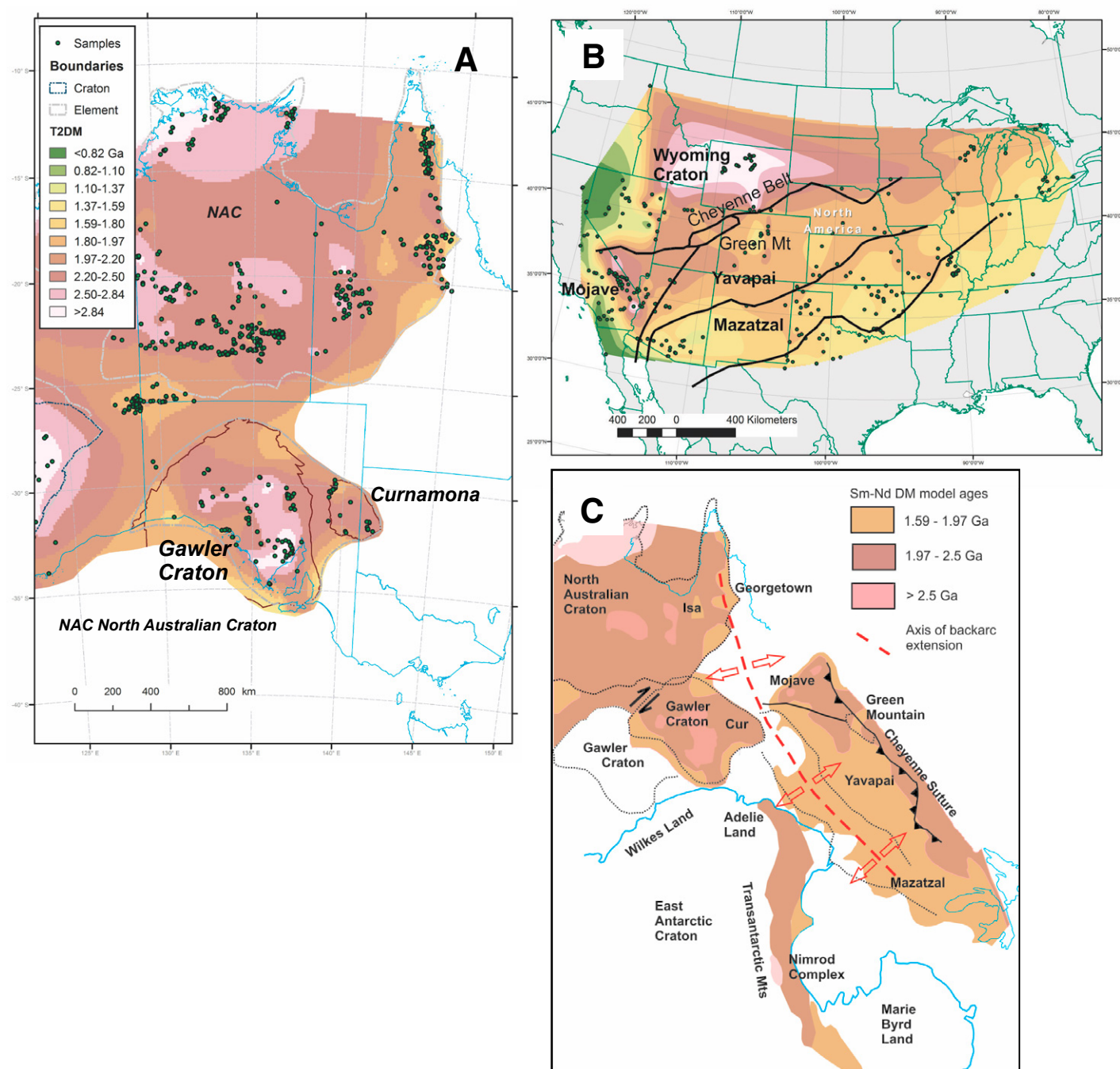


Figure 3. Interpolated Nd two-stage depleted mantle model age maps for (A) Proterozoic eastern Australia, (B) southern United States, and (C) reconstructed Australian-Antarctic margin prior to collision with western Laurentia. All data from felsic magmatic rocks compiled from published data (Table DR2). Note that the model ages on opposing sides of the extensional backarc basin in C are mirror images of each other and range back to the Archean, consistent with rifting and melting of a common substrate. Images were created in ArcGis using Natural neighbors, with Natural Breaks (10 intervals; for discussion, see Champion and Huston, 2016). To facilitate easy comparison, intervals for Australia manually entered to match the U.S. intervals and color ramp. Australian isotopic data sourced from Geoscience Australia (Champion, 2013; Champion and Huston, 2016); U.S. data from Barnes et al., 2002, 1999; Bennett and DePaolo, 1987; Bickford et al., 2015; DePaolo, 1981; Farmer and DePaolo, 1983, 1984; Frost et al., 1998, 2006; Nelson and DePaolo, 1985; Rämö and Calzia, 1998; Antarctica data from Mikhalsky, 2008. Two-stage model ages were calculated assuming a $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.11. Note only single stage model ages used for the data of Bickford et al. (2015), where isotopic ratios were not reported. Differences between single and two stage model ages are dependent on the age of the igneous rock and deviation from the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.11. Inspection of the two shows 90% of values have a difference of 200 Myr or less.

The Mojave Province represents the more outboard component of this system (Fig. 3C) and was intruded by calc-alkaline granites between 1790 Ma and 1730 Ma (Bennett and DePaolo, 1987; Duebendorfer, 2015; Holland et al., 2018; Wooden et al., 2013). These granites once formed part of a magmatic arc and have Nd isotopic signatures consistent with either the incorporation of older continental crust or formation of the province at a convergent margin developed in part above Archean lithospheric mantle or younger mantle enriched by fluids liberated from Archean subducted sediments (Holland et al., 2018; Wooden et al., 2013).

In contrast, the Yavapai and Mazatzal provinces are less isotopically evolved and more juvenile in composition, traits thought to reflect magmatic arc formation on oceanic or very thin continental crust (Amato et al., 2008; Bickford and Hill, 2007; Whitmeyer and Karlstrom, 2007). A decrease in Sm-Nd DM model ages from one province into the other is nevertheless still evident (Fig. 3), consistent with either an accretionary margin origin or formation through backarc extensional processes. Favoring the latter is a near total absence of igneous rocks of intermediate calc-alkaline composition normally expected in an arc environment (Bickford and Hill, 2007). Instead, as in the Mojave Province and basins of Proterozoic eastern Australia and Antarctica, basalt and rhyolite predominate, and magmatism is overwhelmingly bimodal in composition and more in keeping with emplacement in an extensional setting. Andesite and other rocks of unequivocal magmatic arc origin are largely confined to parts of the Yavapai Province immediately south of the Cheyenne Suture (Bickford and Hill, 2007) and sensibly plot in the continental arc field well above the MORB-OIB array in Pearce (2014) discrimination diagrams (Fig. 2B). Their 1780–1760 Ma ages (Duebendorfer, 2015; Whitmeyer and Karlstrom, 2007) are a good match for granite intrusion during the earlier stages of basin formation in the Mojave Province and Leichhardt Superbasin (Fig. 1B), pointing to some form of linkage or common tectonic driver. Conversely, younger 1740–1725 Ma basalts from the Yavapai Province and 1680–1650 Ma basalts from the Mazatzal Province mostly plot much closer to the MORB-OIB array (Fig. 2B) and are not obviously part of the same arc assemblage, as already argued by Bickford and Hill (2007). These rocks are also extensively hosted and overlain by thick sequences of quartzite and other shallow water sedimentary rocks more commonly found in intracontinental rift settings (Jones et al., 2009). In character, timing and composition they bear some similarity to basalts emplaced between 1690 Ma and 1655 Ma in the Calvert Superbasin, again indicating that magmatism and related events in these now widely separated basinal sequences and crustal provinces did not occur in isolation of each other but were connected through shared plate tectonic processes.

Increasingly important in this regard and key to understanding the progression of tectonic events on both continental blocks is subduction rollback and the common record of backarc extension left behind. A backarc extensional setting and history of normal faulting best explains the thick accumulations of rhyolite and super mature quartzite mapped throughout the Mazatzal and southern Yavapai provinces (Jones et al., 2009), whereas Nd and Hf isotopic data for rhyolites and other magmatic rocks exposed throughout the Yavapai Province increasingly point to melt sources in pre-existing, albeit highly attenuated older ca. 1850 Ma continental crust (Bickford and Hill, 2007; Bickford et al., 2015). No less importantly, many of these same magmatic rocks have inherited an abundance of older zircons, either as individual xenocrysts or cores to younger magmatic grains, that yield 1862–1814 Ma ages (Bickford et al., 2015) in the same range as 1870–1840 Ma basement granites and felsic gneisses in Paleoproterozoic eastern Australia (Bierlein et al., 2008, 2011). Such striking similarities are unlikely to be coincidental, instead reaffirming suggestions made here and elsewhere (Gibson et al., 2018) that the provinces of southern Laurentia originated in Australia and were built on a common older basement dating

back to the early Paleoproterozoic or even earlier as would already seem clear from comparisons of the Sm-Nd DM ages (Fig. 3). Deep seismic reflection images confirm that much of Proterozoic eastern Australia is still underlain by highly attenuated or thinned older basement rocks and there is no reason why fragments of this older crust could not have been transferred to Laurentia during collision along with the overlying backarc basinal sequences. Alternatively, this shared basement may always have formed part of the Trans-Hudson-Penokean Orogen of North America as already proposed (Bickford and Hill, 2007) and been simply overridden during collision-related thrusting, although, if this is indeed the case, it is interesting to note that rocks of the same age and arc-like character occur more widely in the Wopmay Orogen east of Bonnetia in northwest Canada (1870–1840 Ma Great Bear Magmatic Arc) (Hildebrand et al., 2010) and in granites and felsic gneisses of the Kalkadoon-Leichhardt belt and Donnington Suite in eastern Australia. Besides providing an additional piercing point for supercontinent reconstructions, correlation of these rocks would further suggest that the separation of eastern Australia-Antarctica from Laurentia could not have occurred any earlier than 1840 Ma.

DISCUSSION

Other than Bonnetia in northwest Canada for which an exotic Australian origin is increasingly proposed (Furlanetto et al., 2016; Thorkelson and Laughton, 2016), similarities between the rocks of Proterozoic eastern Australia-Antarctica and southern North America have long been put down to co-location and formation along a single accretionary convergent margin and/or within the same backarc basinal setting (Betts et al., 2016, 2008; Karlstrom et al., 2001). Central to these interpretations is an assumption that all accreted terranes and basinal sequences originated along strike from one another on the same tectonic plate made up of conjoined ancestral Australia and Laurentia. Terrane accretion along this shared margin is thought to have been driven by north- or south-dipping subduction with successively younger arc and backarc assemblages formed along or outboard of the continental margin assembled and/or accreted during subsequent collisional events. Collisional events reported at 1710–1680 Ma (Yavapai Orogeny) and 1650–1600 Ma (Mazatzal Orogeny) (Whitmeyer and Karlstrom, 2007) have no direct counterpart in Australia but overlap the age of extensional deformation and late-onset basin inversion and folding in the Calvert and Isa superbasins and correlative Willyama Supergroup at 1650–1640 Ma (Riversleigh Event) and 1620–1580 Ma (Isan/Olarian Orogeny). A collisional origin for both Australian events has been proposed (Gibson et al., 2018, 2017) and matching orogenic events have been recognized in the Transantarctic Mountains (Nimrod Complex) and Mojave Province (Goodge and Fanning, 2016; Wooden et al., 2013). Moreover, as in Australia, deformation in the Mojave Province at 1650–1640 Ma was accompanied by crustal thickening and concomitant change in magmatic style and composition. Besides a subsequent absence of younger basaltic rocks (Fig. 1B), S-type granites became increasingly more abundant, whereas, prior to 1650 Ma, A- and I-types predominated (Bennett and DePaolo, 1987; Goodge and Fanning, 2016; Withnall and Hutton, 2013; Wooden et al., 2013). Given that the Mojave province is more isotopically mature than the other two Laurentian provinces and was built on older continental crust, including exposed 1840 Ma felsic gneisses (Elves Chasm), it bears the most resemblance to Proterozoic eastern Australia and records (Fig. 1B) almost all of the same peaks in granite magmatism or magmatically induced tectonism at ca. 1780 Ma, 1760 Ma, 1740 Ma, 1700 Ma, and 1670 Ma (Condie, 1987; Holland et al., 2018; Strickland et al., 2013; Whitmeyer and Karlstrom, 2007; Wooden et al., 2013). Bimodal magmatism in the Mazatzal province at 1630–1620 Ma (Amato et al., 2008), coeval with the emplacement of rhyolite in the Isa

superbasin, would further suggest that the range of shared magmatic peaks extends to younger parts of the stratigraphic succession in both continents. An along-strike origin and common plate tectonic setting for the rocks of southern Laurentia and Proterozoic eastern Australia-Antarctica therefore appears completely plausible, although as argued here this need not imply that the former were indigenous to ancestral North America or formed along the same plate margin as their Australian-Antarctic counterparts. Instead, the many shared attributes of these rocks are a legacy of formation along the originally opposing Australian-Antarctic margin (Fig. 4) whose tectonic setting and evolution from 1800 to 1600 Ma provide a no less compelling explanation as to their formation and origins.

Co-location of the arc and backarc assemblages of southern Laurentia inboard of the same west-dipping subduction zone that formed the backarc basins of Paleoproterozoic eastern Australia-Antarctica provides answers to two interrelated and fundamental questions: 1) the remarkably similar timing and periodicity of events in two now widely separated continents, and 2) the whereabouts of the magmatic arc that formed contemporaneously with backarc extension from 1800 to 1655 Ma along the Australian-Antarctic margin but which appears to no longer reside in either Australia or Antarctica. Similarities in timing might alternatively be explained as the result of far-field forces operating at plate scale, but this argument is increasingly difficult to sustain in light of other aspects of the shared geology, including matching early intrusive-related low pressure–high temperature metamorphism and superposed anticlockwise pressure–temperature–time paths consistent with periodic crustal thickening followed by extensional exhumation and isobaric cooling (Boger and Hansen, 2004; Grambling et al., 1989; Pourteau et al., 2018; Rubenach et al., 2008). A more likely scenario is that the Laurentian provinces represent the more outboard and distal component of the same arc-backarc system that developed along the Australian-Antarctic margin from 1800 to 1655 Ma (Fig. 3C) and underwent deformation and metamorphism at similar times. Early deformation across all regions was for the most part extensionally driven as evidenced by coeval bimodal magmatism, although by ca 1650 Ma, the subducting slab was either no longer rolling back or had begun to advance owing to the arrival of Laurentia at the trench. Arc-continent collision ensued during the course of which the more distal components of the arc-backarc system, including the magmatic arc itself, were thrust-imbricated and emplaced, along with any remaining underlying Australian-Antarctic continental basement, over the incoming Laurentian margin (cf. Whitmeyer and Karlstrom, 2007). Alternatively, the still thermally weak backarc basin may have collapsed first with the arc rocks initially thrust over the Australian-Antarctic margin ahead of full continent-continent collision commencing ca. 1620 Ma. During this terminal event, the three Laurentian crustal provinces were transferred to Laurentia and the two continental blocks remained together, sharing a common post-collisional geological history until the breakup of Rodinia several hundred million years later. Importantly, as with most previous tectonic models for these rocks (e.g., Betts et al., 2016; Whitmeyer and Karlstrom, 2007), all three terranes originated outboard of the Laurentian margin, except that in the interpretation presented here there was no along-strike continuity of subduction from Laurentia into Australia-Antarctica and the latter had already split from ancestral North America before subduction commenced. This is an important distinction because it precludes any physical connection between Laurentia and Australia-Antarctica from at least 1800 Ma until the first collisional event at 1650 Ma, the time when the crustal provinces of southern Laurentia are thought to have first begun to assemble (Amato et al., 2008; Whitmeyer and Karlstrom, 2007). Reconstructions of the Nuna supercontinent that have Laurentia juxtaposed against Paleoproterozoic eastern Australia-Antarctica from 1800 Ma until at least 1650 Ma, if not 1620 Ma, may have to be revised.

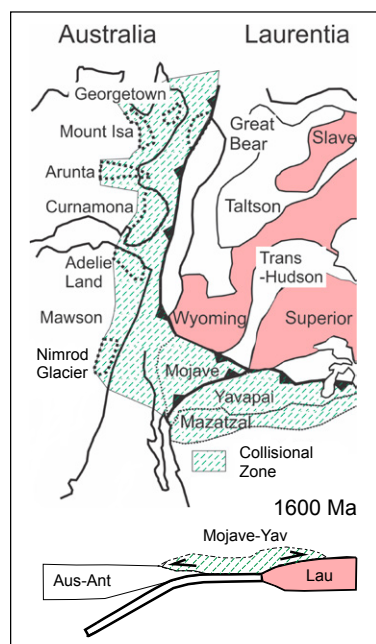


Figure 4. Ocean basin closure and onset of collision between Laurentia and opposing Australian-Antarctic leading to obduction of the intervening magmatic arc and more outboard components of the contemporary backarc basin over the North American plate margin and its Archean substrate (Wyoming Craton). Collision produced a doubly divergent orogen with thrusting directed toward the continental interiors of both continents (Gibson et al., 2017).

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